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OPENING DYNAMIC CHARACTERISTICS OF A 32-FT RINGSLOT PARACHUTE, STIFFNESS INDEX 0.24, AND A 45.2-INCH MODEL, STIFFNESS INDEX 0.40

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UNIVERSITY OF MINNESOTA

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OPENING DYNAMIC CHARACTERISTICS OF A 32-FT RINGSLOT PARACHUTE, STIFFNESS INDEX 0.24, AND A 45.2-INCH MODEL, STIFFNESS INDEX 0.40

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FOREWORD

This report was prepared by the Department of Aerospace Engineering and Mechanics of the University of Minnesota in compliance with U. S. Air Force Contract No. F33615-68-C-1227, "Theoretical Deployable Aerodynamic Decelerator Investigations," Task 606503 "Parachute Aerodynamics and Structures," Project 6065, "Performance and Design of Deployable Aerodynamic Decelerators," Prof. H. G. Heinrich, Principal Investigator. The work on this report was performed between 16 December 1967 and 30 December 1971.

The work accomplished under this contract was sponsored jointly by U. S. Army Natick Laboratories, Department of the Army; Bureau of Aeronautics and Bureau of Ordnance, Department of the Navy; and Air Force Systems Command, Department of the Air Force, and was directed by a Tri-Service Steering Committee concerned with Aerodynamic Retardation. The work was administered under the direction of the Recovery and Crew Station Branch, Air Force Flight Dynamics Laboratory, Air Force Systems Command, Mr. James H. DeWeese was the project engineer.

The study was conducted in cooperation with Mr. Robert A. Noreen and several students of Aerospace Engineering at the University of Minnesota. The authors wish to express their gratitude to all who rendered their services to the accomplishment of this work, especially to Mr. DeWeese for his cooperation and guidance.

This report was submitted by the authors in January, 1972.

This technical report has been reviewed and is approved.

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13. ABSTRACT

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The projected area-time history during the inflation of the 32-ft ringslot parachute, obtained from full size parachute tests, was compared with those of the model ringslot parachute with a stiffness index of 0.40. The area-time characteristics of the model were obtained in wind tunnel tests. Both area-time histories are nearly identical.

Also, velocity-time and opening force-time histories of the model were determined from wind tunnel tests. In order to study the effect of varying mass ratio and surface loading, a number of tests were conducted in which the suspended weight and the parachute model were ejected vertically downward from a compressed air catapult. In these tests the suspended weight was 0.4 of that of the wind tunnel tests. The smaller suspended weight caused a reduction of maximum opening force and a peak force shift to earlier time points.

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The stiffness characteristics of full size and model parachutes can be expressed as stiffness indices. An example is given in which a conventionally built ringslot model parachute has a stiffness index of 1.0. A very flexible model was developed with 0.4 stiffness index while a geometrically similar 32-ft ringslot parachute had an index of 0.24. The design details of the flexible model are described.

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TABLE OF CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (CONT.)

SYMBOLS

C	effective porosity
C_D	drag coefficient
D	diameter
D_{max}	maximum width of the suspended strip specimens or model canopies
$D_{p_{max}}$	maximum projected diameter of the inflated parachute
F	force
g	gravity
L	characteristic length when used in stiffness index
m	mass
S	area
S_p/S_o	dimensionless projected area
T	dimensionless time, $T = t/t_f$
t	time
v	velocity
$V_w - V/V_s$	dimensionless relative velocity
W	weight
w_{cl}	weight of cloth per ft^2
ρ	density
η	canopy stiffness index, $\frac{D_{max}}{L} \cdot \frac{W_c}{S_o\, w_{cl}}$

Subscripts:

a	apparent
c	canopy
cl	cloth
f	filling

i	included, inlet
o	nominal, total
p	parachute, projected
s	suspended, snatch when used with velocity
ST ST	steady state
w	wind tunnel
	Other symbols, when used, are defined in the text.

I. INTRODUCTION

It has frequently been mentioned that canopy flexibility or stiffness probably influences the performance characteristics of full size and model parachutes. Recently, numerical data from wind tunnel tests became available which clearly indicated the influence of stiffness or flexibility (Refs 1,2). In the course of this study a stiffness index, η, was established which relates the ratio of the diameter of the suspended, deflated canopy, D_{max}, to the nominal diameter, D_o, multiplied by the ratio of the weight of the finished canopy to the weight of the canopy cloth having the same area S_o. It was found that conventionally fabricated parachute models of solid flat parachutes had stiffness indices three to ten times that of a 28-ft solid flat parachute. The stiffness index of a conventionally built ringslot parachute model with a 45.2-inch diameter was four times as high as that of a 32-ft ringslot parachute with the same principle design parameters. It was then shown how to build more flexible and lighter ringslot models, and a model was made whose stiffness index was merely four-tenths (0.4) that of a conventional model of the same size.

The second portion of the referenced study showed that the more flexible solid flat models approached the steady-state profile of full size canopies better than did the stiffer models. Also, the function of projected area to inflation time of the more flexible model very closely approached the same characteristic of the full-sized parachute. The force-time characteristics during inflation showed between 30 and 40 per cent lower peak forces than stiffer models of the same size under the same test conditions.

In view of these findings, the following study was performed in which several performance characteristics of a highly flexible 45.2-inch ringslot parachute were compared with corresponding observations obtained from tests of a 32-ft ringslot parachute with approximately the same total porosity.

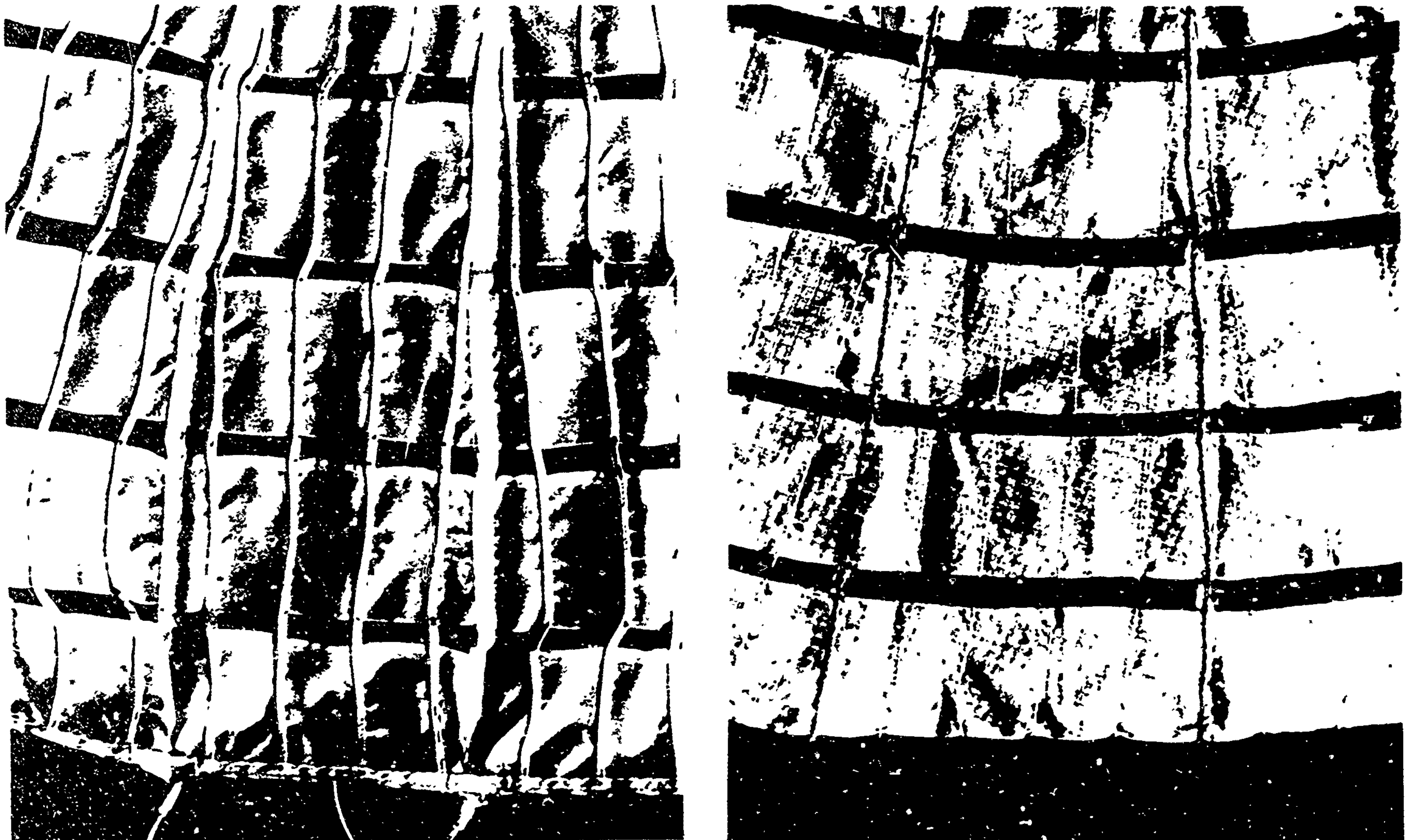
II. MODEL CONSTRUCTION AND STIFFNESS INDICES

Conventional ringslot parachute models consist of a number of triangular gores which are composed of individual sections of standard parachute cloth. These sections are strips of cloth with both edges finished by seams and stitching. The individual gores are joined together along the radial ribbons, and the cloth strips are held in place by vertical bands which are sewn to the cloth strips. Usually the parachute vent as well as the skirt are reinforced by vent and skirt bands. Figure 1-a shows this type of contruction.

This fabrication method provides model canopies which are relatively much stiffer than full-sized parachutes, since the cloth, the ribbons, and the stitching cannot be reduced by the same scale as the diameters of the model and full-sized parachutes. Also, due to the tension in the thread which connects the various portions of the canopy, a so-called sewing take-up is developed which alters the size, shape, and geometric porosity of the canopy. Therefore, it is very difficult to build a model canopy which has the intended geometric porosity and shape. Usually, canopies which are supposed to be flat turn out to be conical.

Furthermore, the sewing take-up is a matter of the skill and individuality of the fabricator, and parachute models of the same size, with identical construction details and designed total porosity but made by different people are generally not alike. This individuality is, of course, very detrimental to the establishment of reliable performance data and jeopardizes the model similarity in view of the full-sized canopy which a model is suppose to represent. As an attempt to reduce these deficiencies, a new model fabrication technique is described in Refs 1 and 2. In particular, the cutting of cloth, webbings, and lines by means of a hot knife proved to be very successful and was made the basis of the model construction described below.

Using a hot knife, two halves of a solid cloth disk were cut from 1.1 oz/yd^2 nylon, MIL-C-7020, Type I, and joined together with a double stitched French seam. The seared circumferential edges eliminated the need for skirt and vent bands. The geometric porosity features of the parachute were then provided by slots cut with the same hot knife mounted on a rotating radial arm. In order to simulate the gores the circumferential cuts were not continuous but radial cloth strips were left, to which the suspension lines were later attached by means of zig-zag stitching. Rows of stitches with adequate thread served as vertical bands. Figures 1-b and 2 show fabrication details and dimensions of the model used in the following study.



a b

Fig 1 Fabrication Details of a Conventional, a, and a more Flexible, b, Ringslot Parachute Model

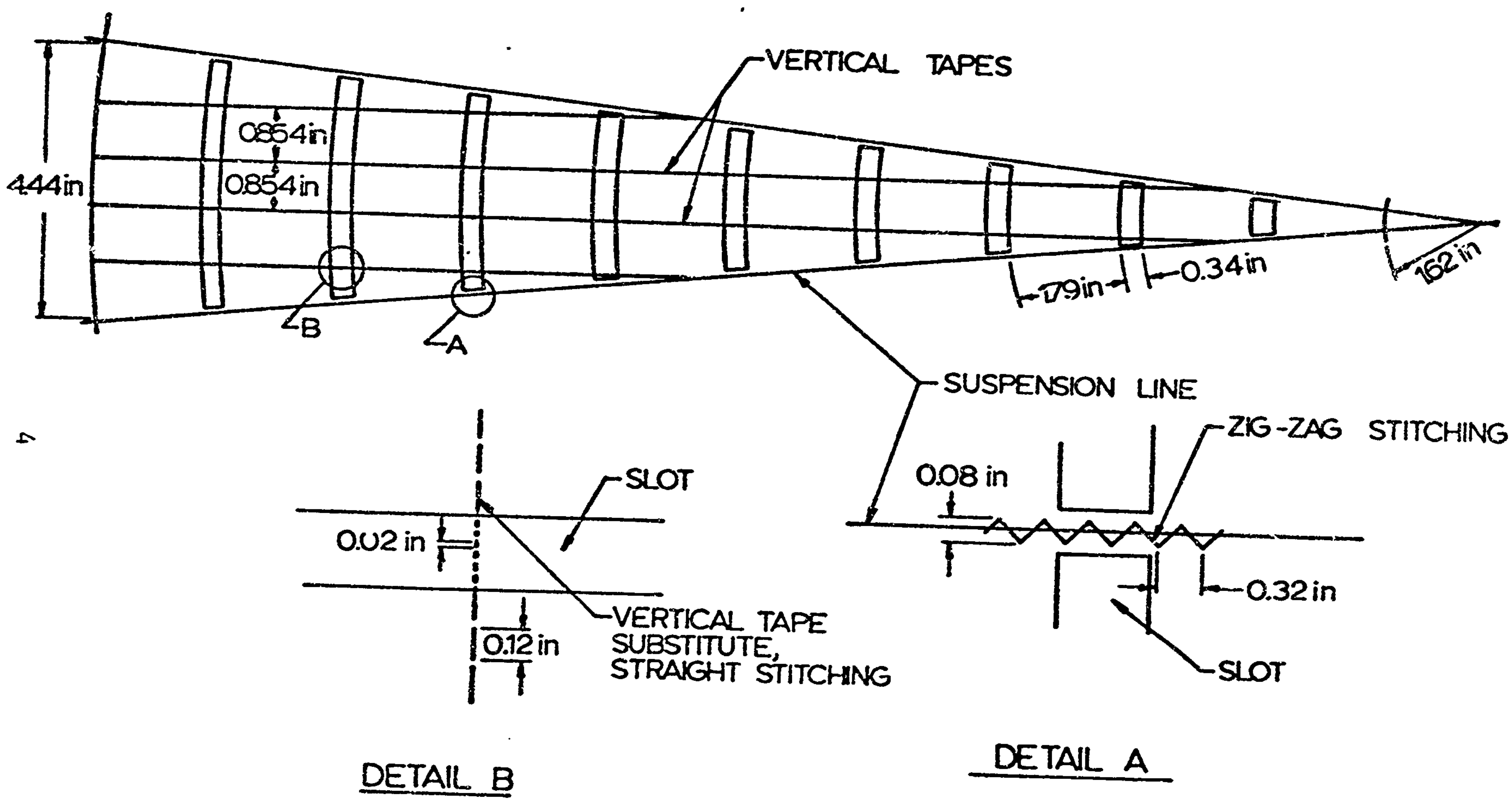


Fig 2 Details of a Ringslot Parachute Gore Utilizing Hot Knife Cut Fabrication Method

This fabrication method provides more accuracy for the porosity requirements and eliminates most of the sewing errors due to thread tension. It is also evident that models made in this manner will have a much lower stiffness index than those built conventionally.

The stiffness index of the 32-ft prototype parachute, its porosity characteristics, and other features as well as the respective features of the models with high and low stiffness indices are shown in Table I.

III. EQUATION OF MOTION AND TEST ARRANGEMENT

The terms which influence the opening dynamics of a parachute can best be recognized by reviewing the equation of motion of an inflating parachute. Then, an attempt will be made to establish these terms by means of wind tunnel tests and to compare them, when possible, with related terms from full size experiments.

For the inflation of a parachute in a wind tunnel, and using the arrangement shown in Fig 3, the equation of motion amounts to

$$(d/dt)\left[(m_s + m_p + m_i)V\right] = D - W_s + F_a + V_w(dm_i/dt) \qquad (1)$$

where F_a is the force because of the apparent mass effect, and $V_w(dm_i/dt)$ represents the momentum of the air trapped in the canopy due to the relative velocity between the parachute and the air in the wind tunnel. Using for the wind tunnel and system velocities V_w and V, respectively, and expressing F_a as

$$F_a = (d/dt)\left[m_a(V_w - V)\right] \qquad (2)$$

the equation of motion can be written

$$\begin{aligned} m_s(dV/dt) = {} & \tfrac{1}{2}\rho C_D S(V_w - V)^2 - W_s + (V_w - V) \\ & \left[(dm_i/dt) + (dm_a/dt)\right] - (m_p + m_i + m_a)(dV/dt) \end{aligned} \qquad (3)$$

The system velocity, V, is positive in the direction of the drag vector and because of the experimental arrangement, dV/dt is by definition always positive. With these terms, the force upon the suspended weight amounts to

$$\begin{aligned} F = m_s(dV/dt) + W_s = {} & \tfrac{1}{2}\rho C_D S(V_w - V)^2 + \\ & (V_w - V)\left[(dm_i/dt) + (dm_a/dt)\right] = \\ & = (m_p + m_i + m_a)(dV/dt) \end{aligned} \qquad (4)$$

An inspection of the right-hand side of Eqn 4 shows the nonsteady terms of the systems velocity V, the area S, the included mass m_i, the apparent mass m_a and the time derivatives of these terms. The equation also includes the drag coefficient C_D which, for the purpose of this study, may be considered to be identical with those known from steady-state experiments. Unfortunately, drag coefficients of parachutes during the nonsteady process of inflation are so far not available.

As shown in Fig 3, the parachute model is connected by means of a cable and pulley system to a weight. During the tests, the model parachute is initially packed in a deployment bag and held at a particular point. The bag is connected to a pilot parachute, which, when released, accelerates the bag and removes it from the canopy when the suspension lines of the model are fully extended. At this instant, the snatch force occurs, and thereafter the canopy begins to inflate. The deployed parachute pulls at the suspended weight, lifts it up, and the canopy moves downstream.

In order to determine the nonsteady terms, the force between parachute and suspended weight was measured by means of a strain gage balance, and the velocity of the suspended weight was recorded by means of a rotating slotted disk and a photocell arrangement. The outputs of the sensor for the force, F, and the system velocity, V, were recorded on an oscillograph. In order to establish the rate of growth of the canopy and to derive the included and apparent mass terms, movie cameras for side and top views were used as indicated in Fig 3. A typical recording diagram is shown in Fig 4, Item a.

The parachute model was geometrically similar to a 32-ft flat ringslot parachute, and its nominal diameter was 45.2 inches, Table I. The suspended weight, W_s, was 1.0 lb, which, in connection with the canopy surface area, yields a surface loading of $W_s/S_o = 0.09 \text{ lb/ft}^2$.

This weight was chosen because under these conditions the inflation of the parachute was completed within the distance of the open section of the wind tunnel. Models with lighter weight passed through the test section before the canopy was inflated.

In view of the wind tunnel and instrumentation capability, initial velocities of 50, 70, and 85 fps were chosen, and with the described test arrangement, these speeds are the snatch velocities of the model parachutes.

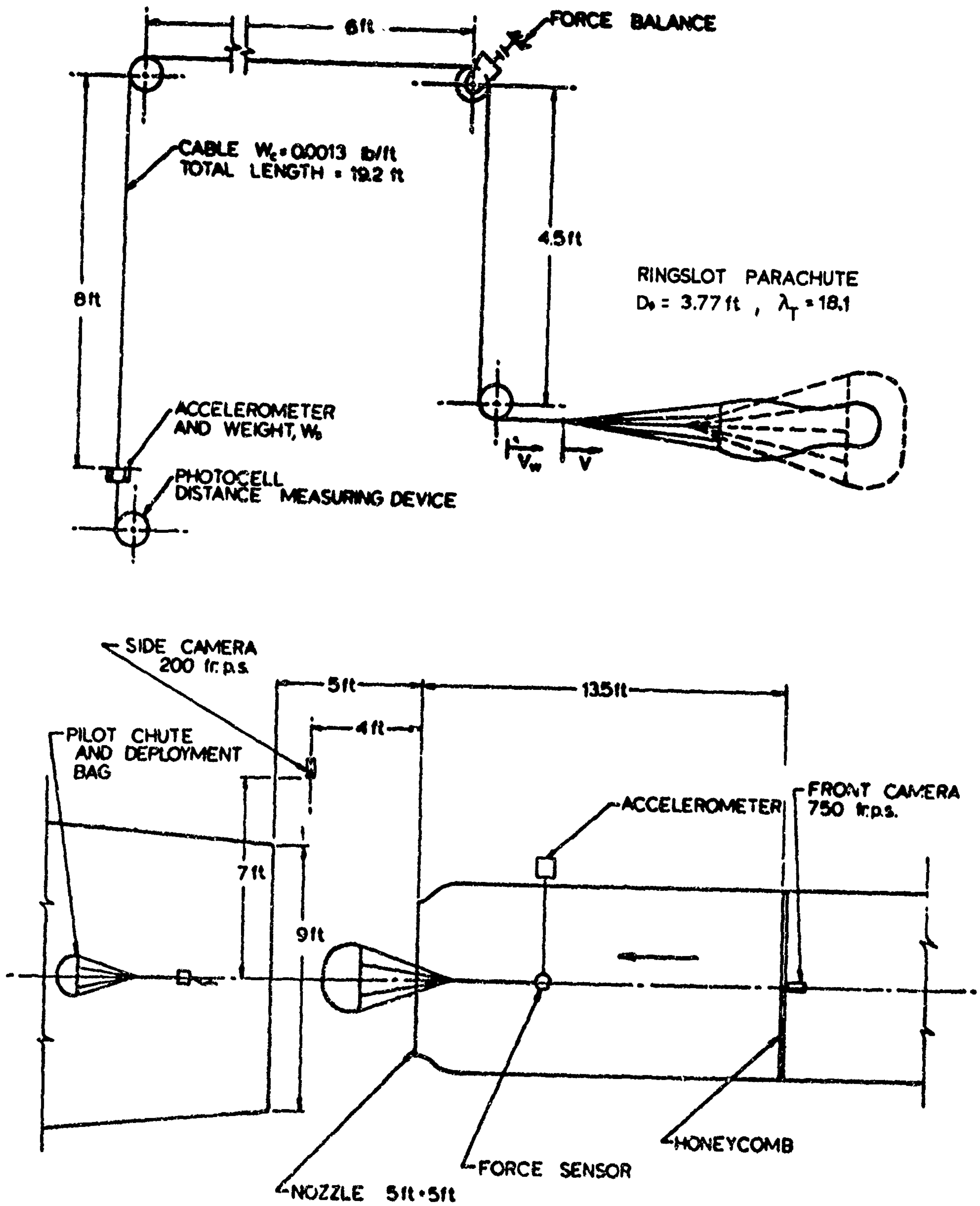
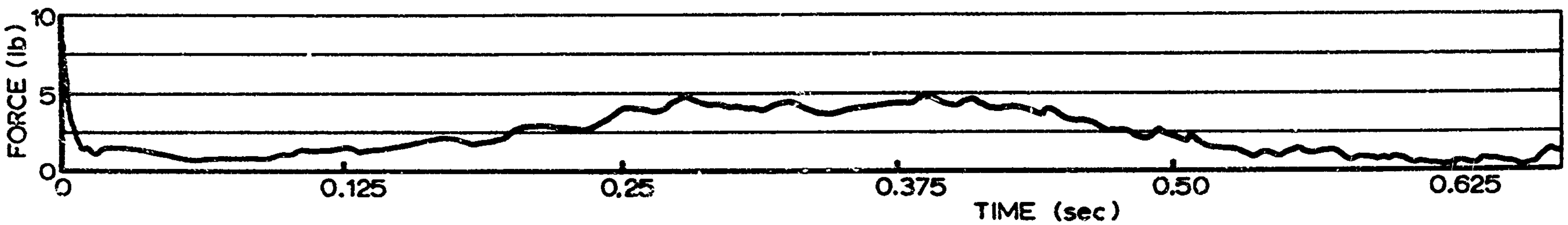
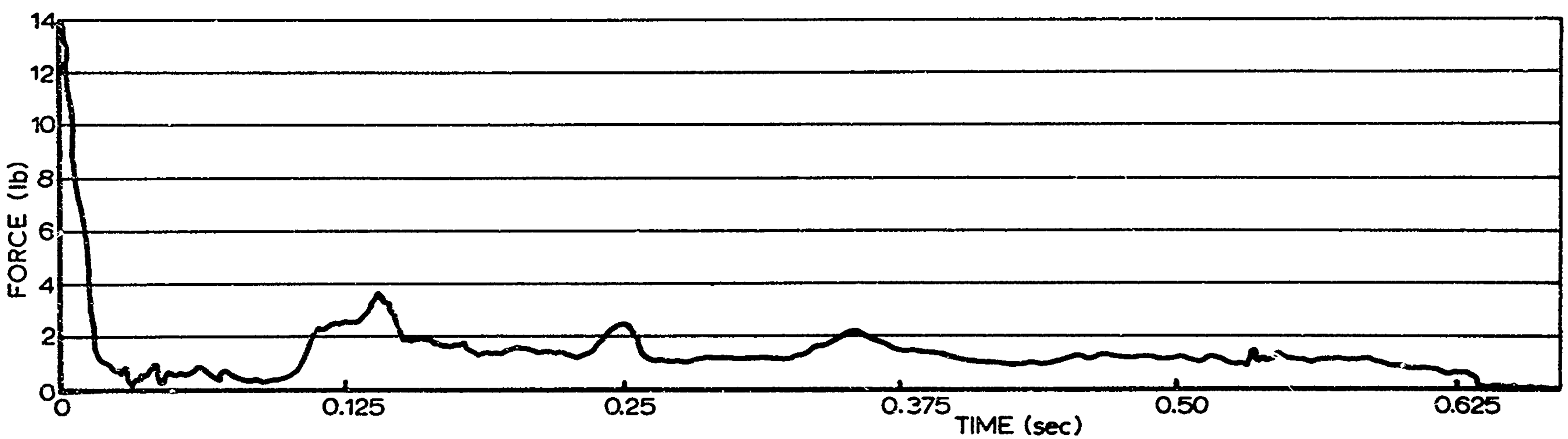


Fig 3 Wind Tunnel Arrangement for Testing Under Finite Mass Conditions



a) INFLATION IN WIND TUNNEL TEST, W_S = 1.0 lb, m_i/m_s 0.3, V_W = 50 fps



b) INFLATION AFTER CATAPULT EJECTION, W_S = 0.4 lb, m_i/m_s = 0.75, V_S = 50 fps

Fig 4 Force-Time Histories of Ringslot Parachute Models with Different Suspended Weights

TABLE I
PHYSICAL PROPERTIES OF MODEL AND PROTOTYPE RINGSLOT PARACHUTES

Parameter	Prototype	Flexible Model	Conventional Model
Nominal Diameter D_o, Ft	32.2	3.77	3.77
Stiffness Index η	0.24	0.40	1.00
Parachute Cloth Specification	MIL-C-7350C Type I	MIL-C-7020 D, Type I	MIL-T-5608E Class A Type V
Nominal Porosity ft^3/ft^2-min	125 ± 25	100 ± 20	150 ± 30
Geometric Porosity λ_g	15.6%	15.0%	7.6%
Total Porosity* λ_T	19.5%	18.1%	12.7%
Canopy Weight W_c, lbs	28.8	0.11	0.35

*Calculated in accordance with USAF TR No. ASD-TR-61-579.

Reviewing the equation of motion one notices that the surface loading, W_s/S_o, and the mass ratio, $(m_i + m_a)/m_s$, appear as functions of time and time derivatives. One has to decide which parameter should be approximately the same as that of the full size parachute tests. Previous studies indicated (Refs 3,4) that the mass ratio and its time derivative can be a significant contribution to the equation of motion. Furthermore, if the stiffness of the model or of the full scale parachute expedites or delays the inflation, the mass-time derivatives will vary accordingly. Therefore, the mass ratio, m_i/m_s, appears to be the more important scaling factor for this study.

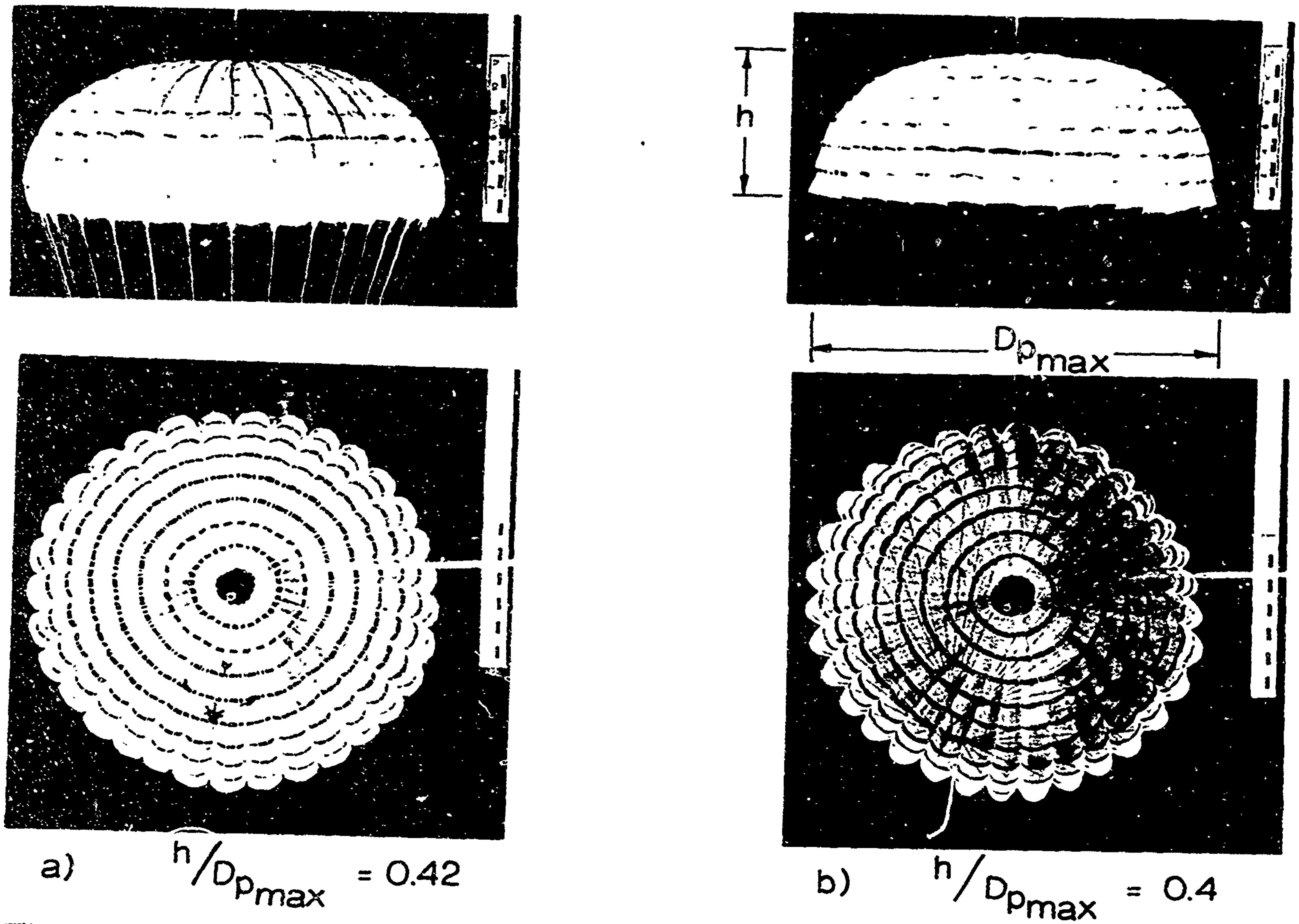
In the scaling process the apparent mass may be neglected because it probably amounts to the same percentage of the included mass (Refs 3,4) in both the full size and the model parachutes.

In order to establish the amount of the included mass, it is then necessary to determine this quantity for the ringslot parachute model which will be used in the experiments.

Figure 5 shows the profiles of the flexible and conventionally built models which are listed in Table I. For comparison, a profile of a full size ringslot parachute is given in Fig 6 (Ref 5). One notices that the flexible model and the full size parachute have practically identical $h/D_{p_{max}}$ ratios and their contours also look alike.

In attempting to determine the included mass of the flexible model, one finds that its side profile indicates neither a perfect ellipsoid nor a hemisphere. With a suspended weight of 1 lb the mass ratios m_i/m_s of the hemisphere and the ellipsoid are 0.35 and 0.29, respectively, and an average value of 0.32 may be a satisfactory approximation. With this information established, the parameters of the opening dynamics of model and comparable prototype tests are listed in Table II. One notices that the mass ratio of the model tests is close to the one of the prototype test at 20,000 ft, while the surface loading data vary by a factor of almost 3. However, as the table shows, increasing the surface loading would lower the mass ratio and vice versa, and at this time it appears to be very difficult to satisfy both conditions.

Because of this difficulty and in view of the reasoning above, the mass ratio was chosen as scaling factor.



a) $h/D_{p_{max}} = 0.42$ b) $h/D_{p_{max}} = 0.4$

Fig 5 Conventional, a, and Flexible, b, Models of a 32-Gore Ringslot Parachute, D_o = 45.2 in

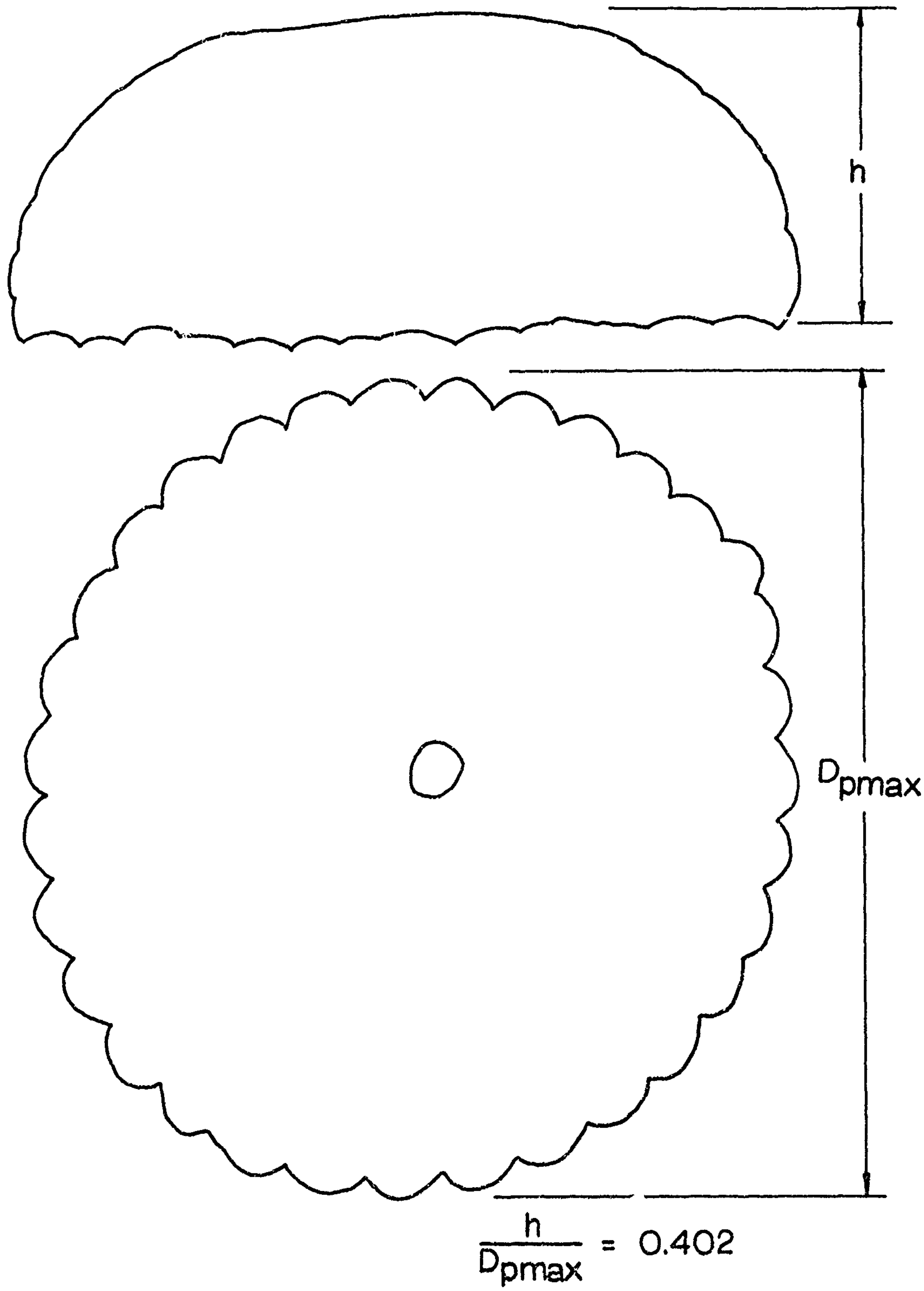


Fig 6 Profiles of Inflated 32-ft Ringslot Parachute (Ref 5)

TABLE II
OPENING DYNAMICS PARAMETERS OF PROTOTYPE AND MODEL TESTS

Parachute	W_s	Run No.	V_s	h (altitude)	m_i/m_s	W_s/S_o
Prototype	226 lb	1301	208 fps	6,000 ft	0.619*	0.25 lb/ft^2
	"	1613	245 fps	13,000 ft	0.498*	"
	"	1046	194 fps	20,000 ft	0.395*	"
Model	1.0 lb	----	50 fps	900 ft	0.320	0.09 lb/ft^2
	"	----	70 fps	"	"	"
	"	----	85 fps	"	"	"

*(Ref 3)

IV. AREA-TIME AND VELOCITY-TIME HISTORIES

As mentioned before, the main purpose of this study was the comparison of performance parameters of a flexible model with those of a 32-ft prototype parachute. Available for comparison are the area-time and force-time histories of the prototype (Refs 3,5). From these two features the area-time characteristic appears to be the better one for comparison. Because in Refs 3 and 4 it was shown that for solid flat parachutes the area-time curves have a certain degree of uniqueness, it may be assumed that for ringslot parachute models a similar uniqueness could be found. If then the average of the area-time curves, obtained at different deployment speeds, agrees somewhat satisfactorily with similarly obtained area-time curves of the prototype, one may conclude that, as far as the area-time relationship is concerned, a certain model similarity does exist.

Furthermore, if one postulates that the canopy shapes of the model and the prototype are geometrically similar for the same projected area ratio, S_p/S_o, the mass-time histories and their time derivatives will be the same. If this could be proven, one would have very valuable information on hand for the prediction of opening forces. A study of this subject is beyond the scope of this investigation, and the argument above may emphasize merely the importance of the comparison of area-time histories of model and prototypes.

Figures 7 to 9 illustrate area-time histories of the flexible ringslot parachute model, and in Fig 10 a related area-time curve of the 32-ft ringslot parachute was taken from Ref 3 for comparison. In model and prototype testing the projected area was recorded by photographic means, and the filling time t_f is the time interval from the instant of snatch until the projected area first reaches the value which the parachute assumes under steady state conditions. The curves, marked average on these and all figures to follow, were calculated using the "least square" method. One notices a fairly good agreement between the results of individual tests organized by initial velocity as well as the averaged values of these velocities among each other. Therefore, a certain degree of uniqueness seems to exist. Also, the comparison between the finally averaged curve of the model tests and the characteristic curve of the prototype parachute shows surprisingly good agreement.

As a conclusion one may state that the very flexible model parachute has nearly the same area-time function as the related prototype. The range of Reynolds numbers involved extends from $1.2 \cdot 10^6$ to $3.7 \cdot 10^7$ whereas the linear scale was 1:8.5.

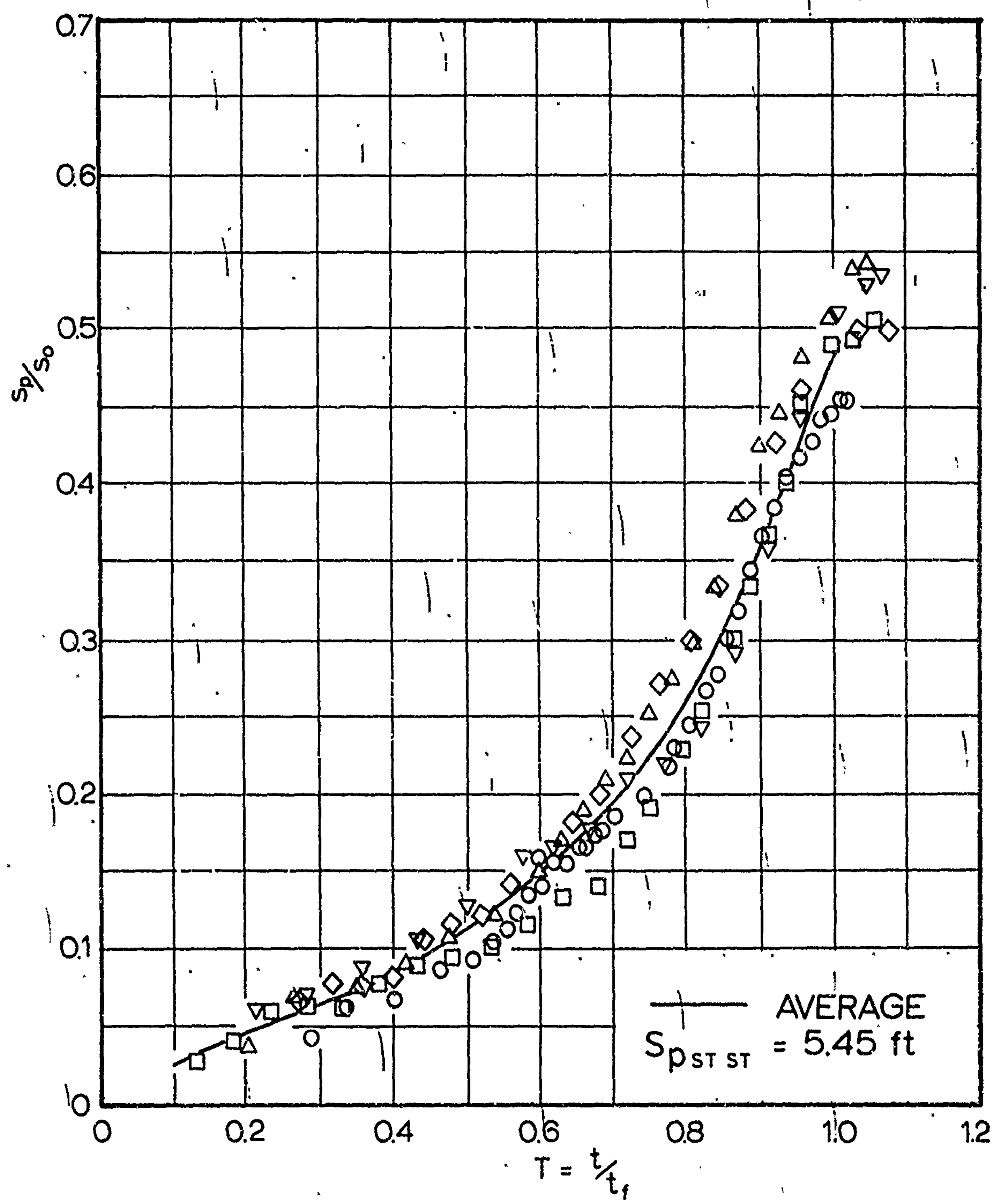


Fig 7 Area-Time History of a Model Ringslot Parachute, $\eta = 0.40$, $D_O = 3.77$ ft, $m_i/m_s = 0.32$, $V_s = 50$ fps

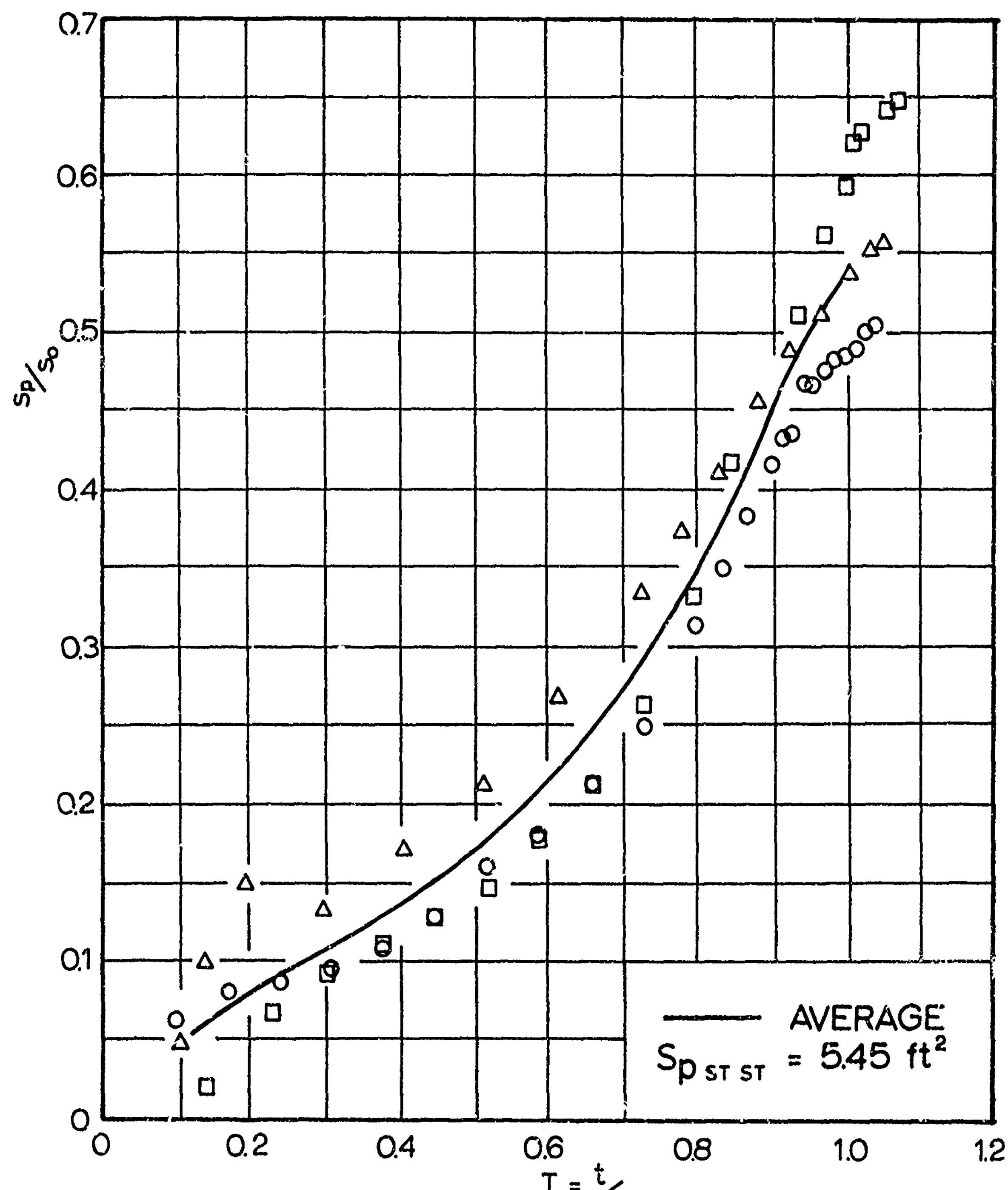


Fig 8 Area-Time History of a Model Ringslot Parachute, η = 0.40, D_O = 3.77 ft, m_i/m_s = 0.32, V_s = 70 fps

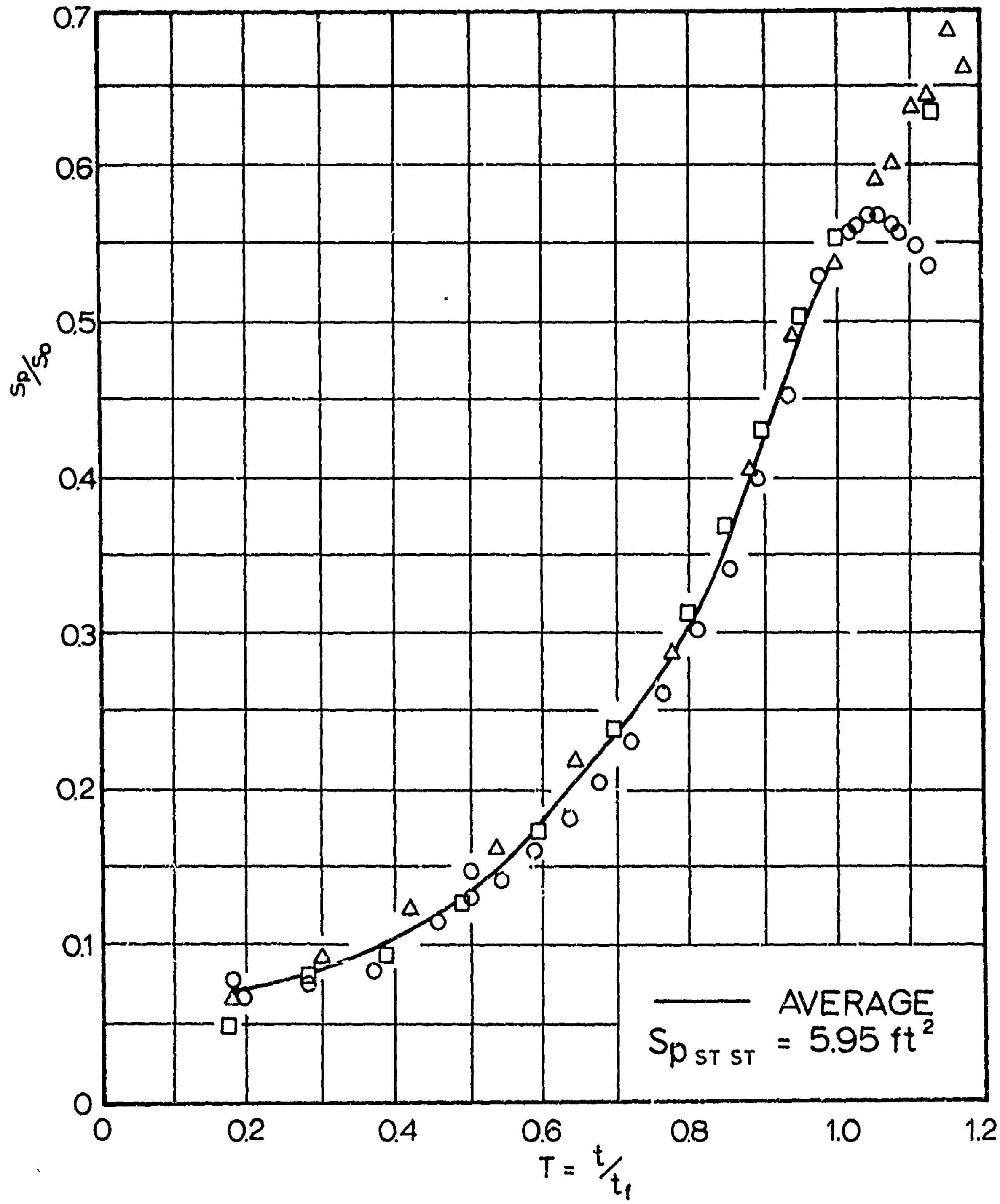


Fig 9 Area - Time History of a Model Ringslot Parachute, η = 0.40, D_O = 3.77 ft, m_i/m_s = 0.32, V_S = 85 fps

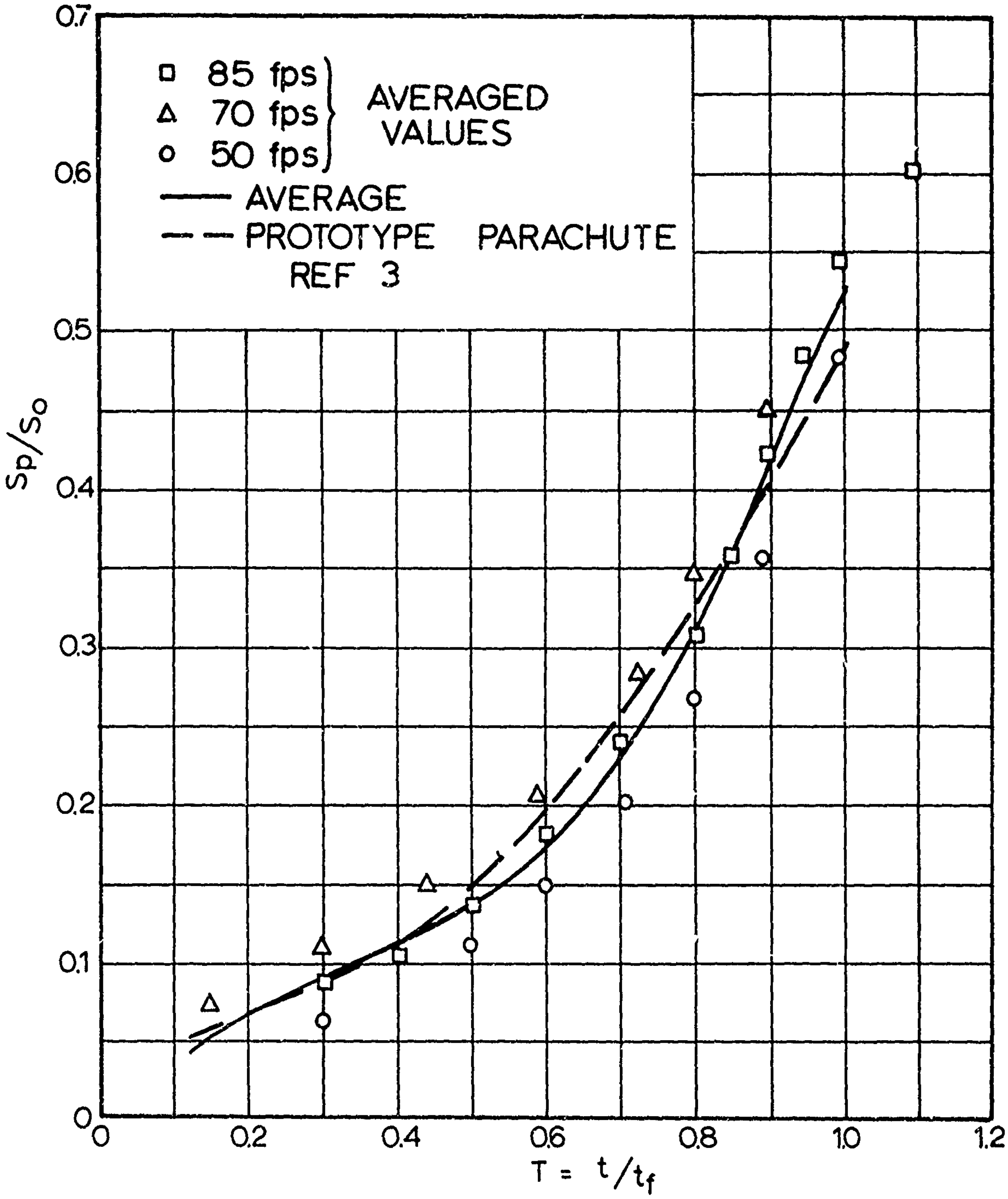


Fig 10 Average Area-Time Histories of Model and Prototype Ringslot Parachutes

Assuming that the mass-time histories are closely related to the area-time relationships, the velocity-time histories may be considered a solution of the equation of motion. The area-time histories indicated a certain degree of uniqueness, and if the postulation above is valid, then the velocity-time histories should also show uniqueness. In determining whether one may assume such a relationship, perhaps as a first approximation, the relative velocities of the flexible model and the surrounding air were determined and presented in Figs 11 to 14.

In Fig 14 one notices a certain dispersion, although the same basic characteristic. In reviewing the presented results, one should not overlook the very short time intervals involved and the fact that small errors lead to significant time shifts. Therefore, one may assume as a first approximation that the presented velocity-time histories do indeed indicate a certain degree of uniqueness. In turn, this may be taken as an indication that the postulation made above has some validity.

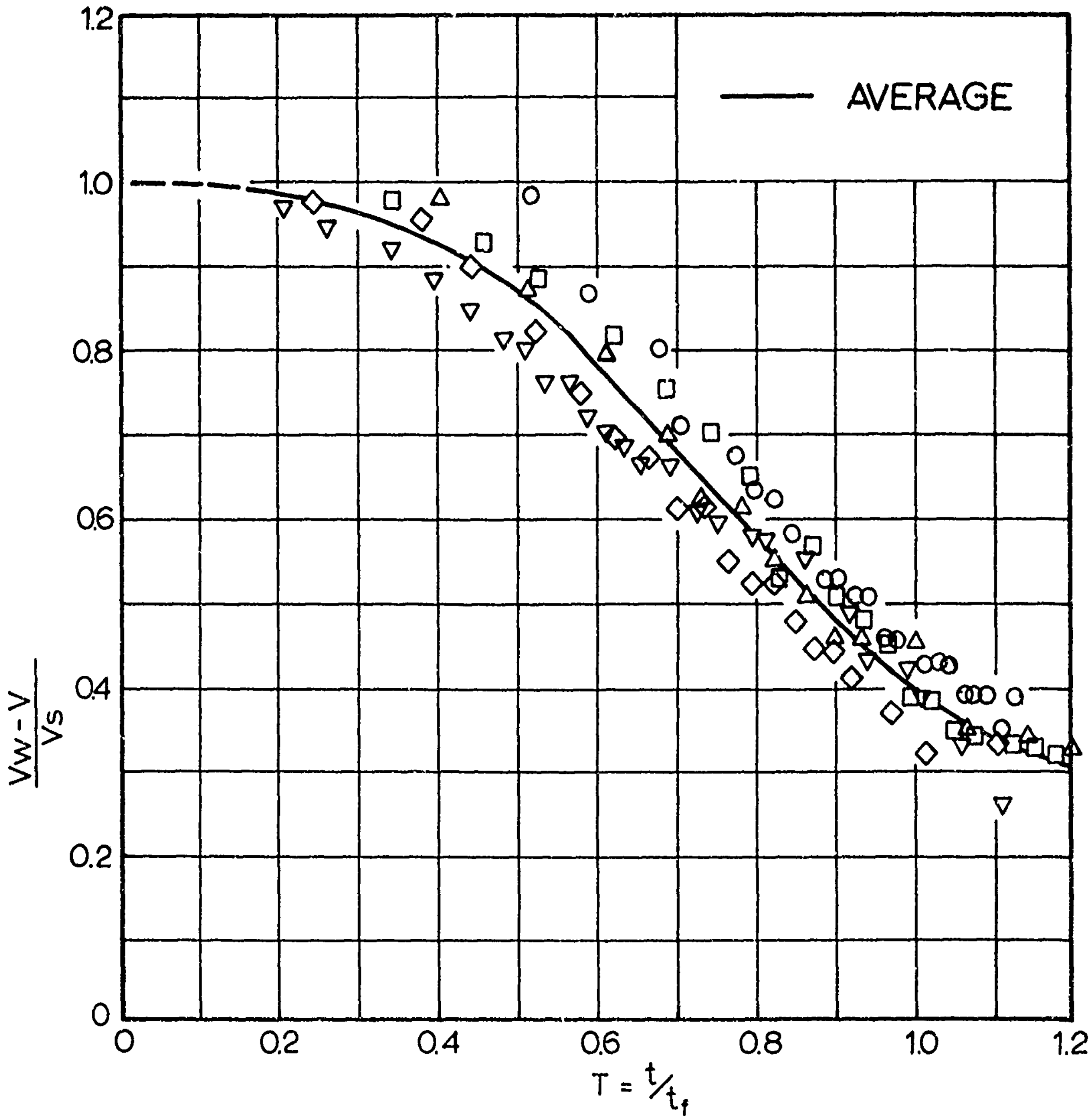


Fig 11 Relative Velocity, 3.77-ft Ringslot Parachute, $\eta = 0.40$, $m_i/m_s = 0.32$, $V_s = 50$ fps

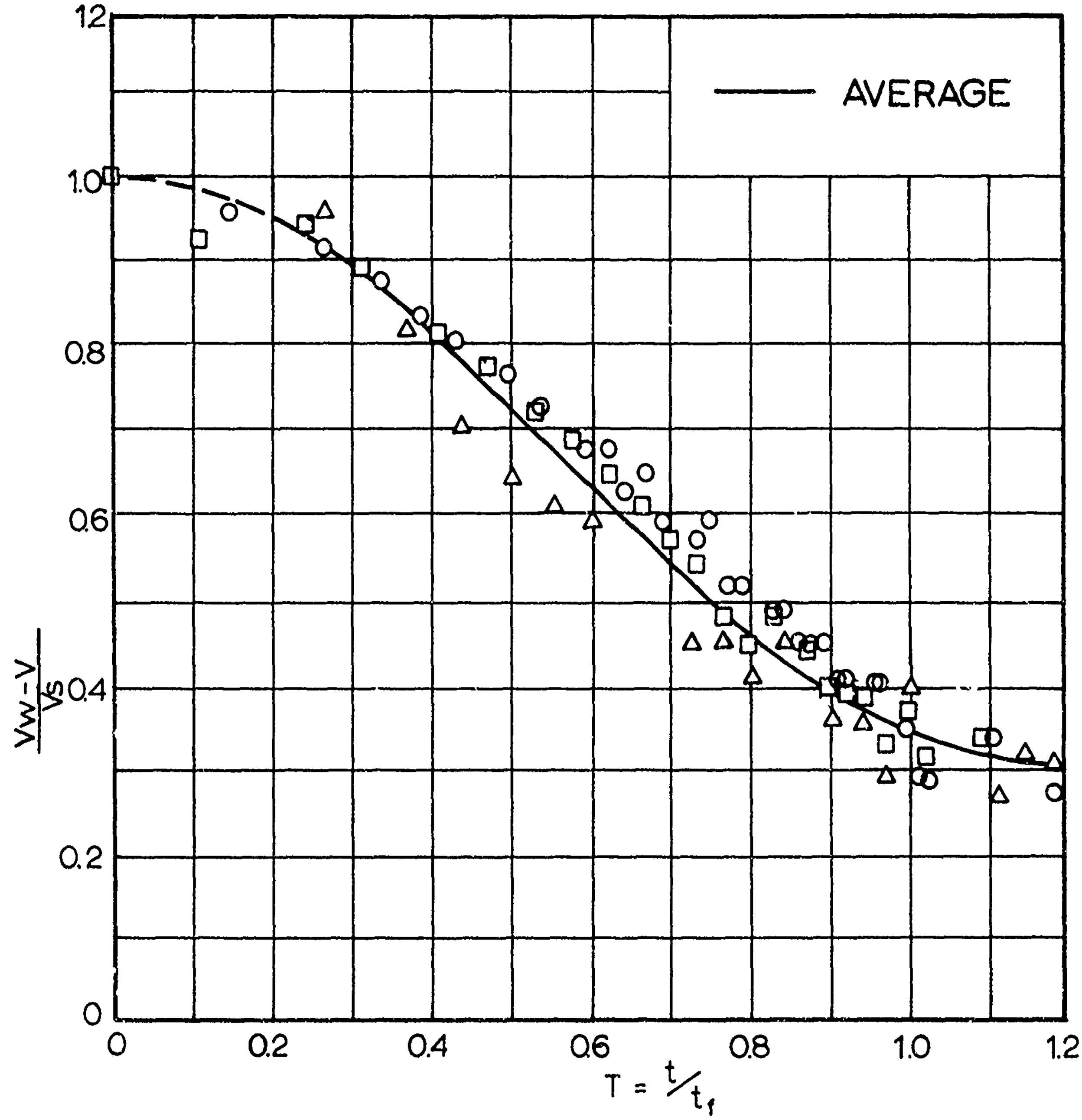


Fig 12 Relative Velocity, 3.77-ft Ringslot Parachute, η = 0.40, m_i/m_s = 0.32, V_s = 70 fps

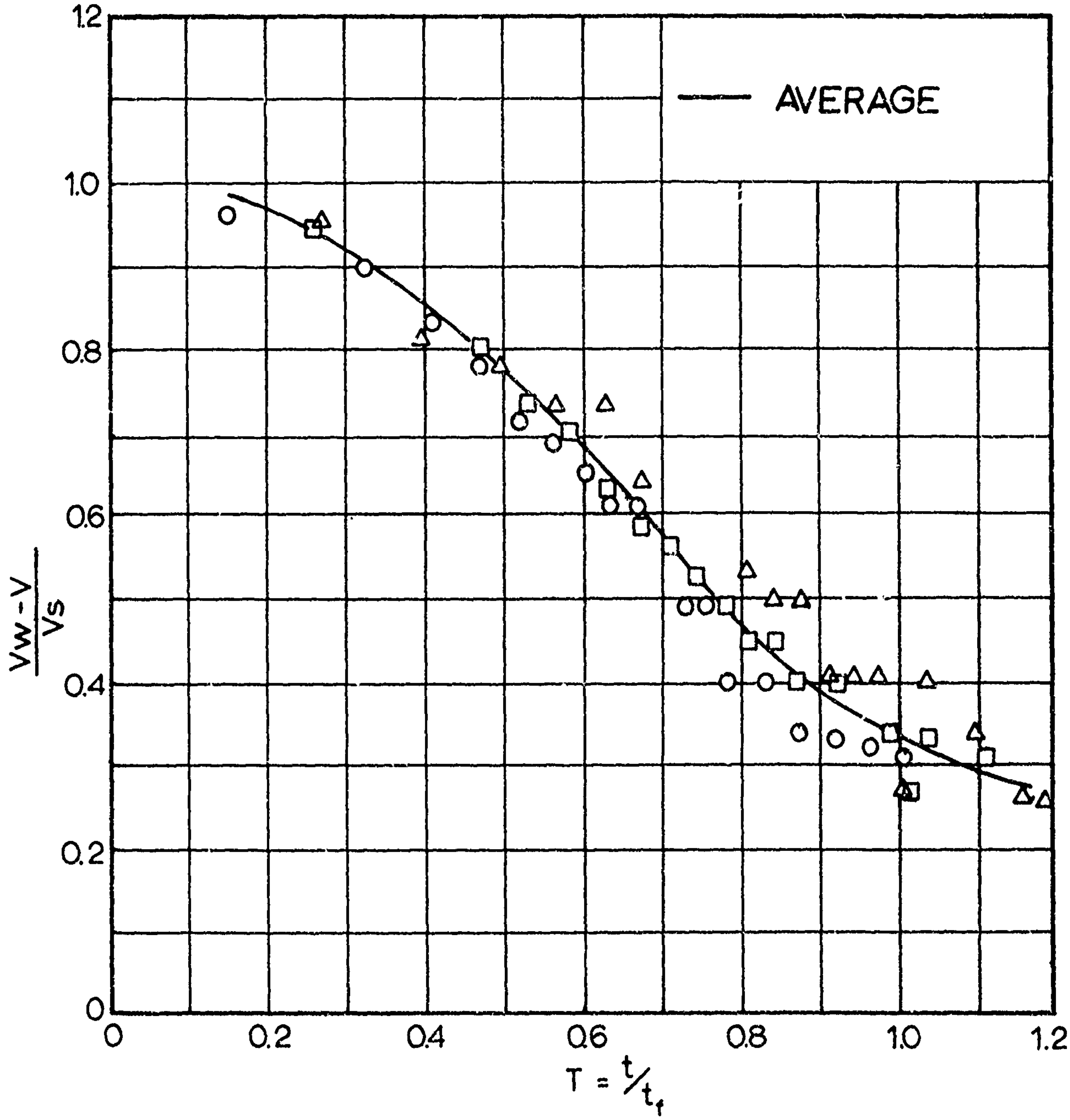


Fig 13 Relative Velocity, 3.77-ft Ringslot Parachute, η = 0.40, m_i/m_s = 0.32, V_s = 85 fps

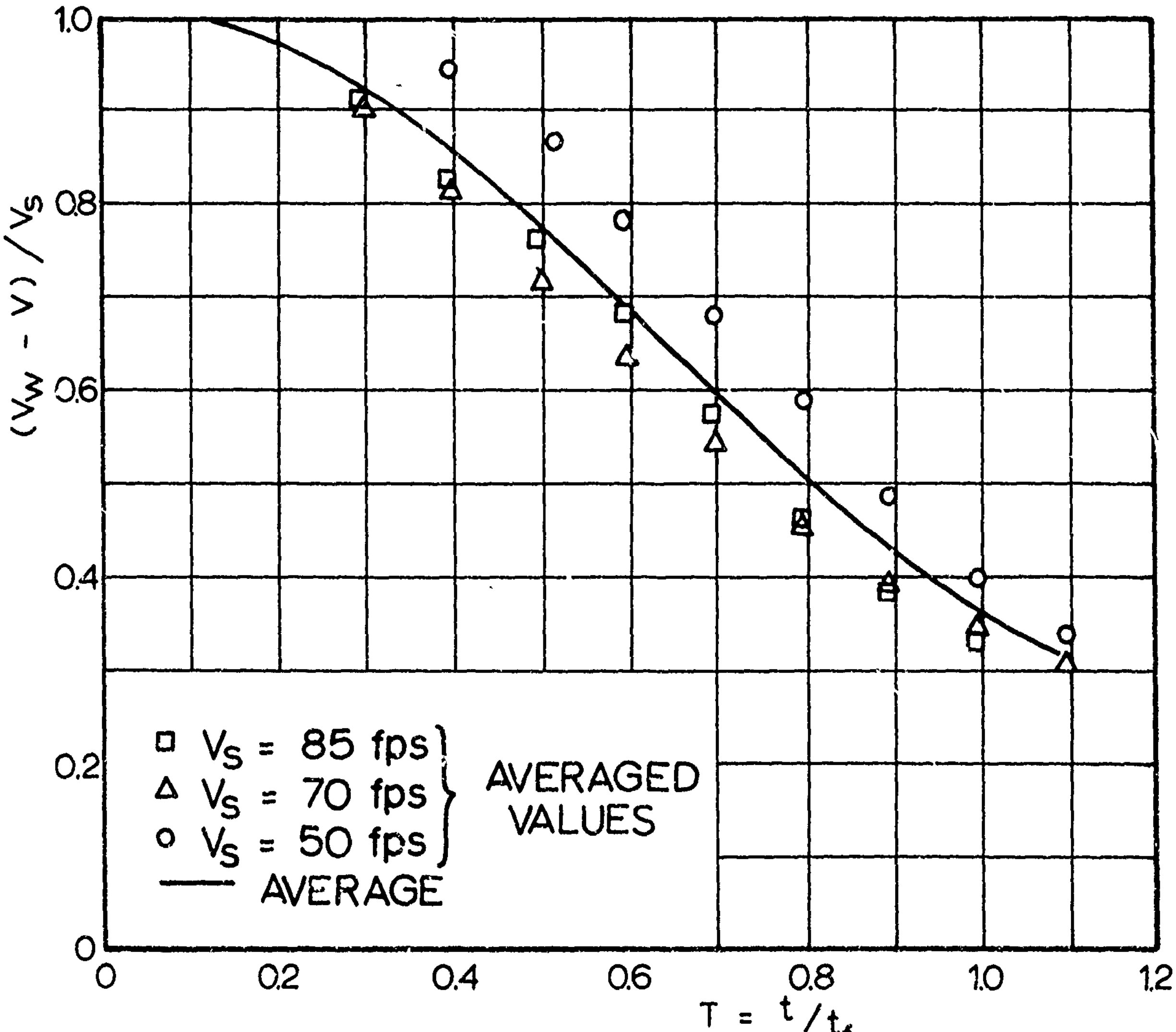


Fig 14 Average Relative Velocity, 3.77-ft Ringslot Parachute, $\eta = 0.40$, $m_i/m_s = 0.35$, $W_s = 1.0$ lb

V. FORCE-TIME HISTORIES

Force-time histories are another solution of the equation of motion, and it is interesting to check if certain identities could be established between model and prototype tests. Therefore, a number of model tests were made in order to establish average force-time curves. These may then be compared with available prototype force-time histories.

Figures 15 to 17 show the results of these wind tunnel tests. One notices dispersion but also characteristics of the averaged curves which are worthwhile to study.

As a simpler characteristic one may note that the maximum forces as well as an average force over the time interval from $0 < T < 1$ increase with increasing snatch velocity. Also the peak force, which occurs at the lowest speed relatively late, moves toward earlier time points when the speed increases. No attempt will be made at this time to analyze or explain this observation. It merely seems to be a well established fact.

Figure 18 shows typical force-time recordings obtained with the prototype. A very obvious difference between these and the recordings obtained from the model tests is the fact that in the prototype tests the peak forces occur very early in the inflation process.

One may think of a number of reasons why this difference occurs. However, following the thought that the mass ratio is a very important parameter, additional model tests were made in which the parachute model was ejected vertically downward by means of a compressed air catapult. The force vs time was recorded by means of instrumentation as described in Ref 6. In these tests the suspended weight was reduced to 0.4 lb giving a ratio of $m_i/m_s = 0.75$. A typical recording of this series of tests is shown in Fig 4, Item b.

Figure 4, Item a, is the recording obtained from wind tunnel tests and is typical for a considerable number of recordings. Figure 4, Item b is just as typical for an approximately equal number of catapult tests. In both types of experiments the model was the same, the deployment bags identical and the speed was the same, namely $V_s = 50$ fps. The only changes were the mass ratio and the surface loading.

At this time, it cannot be shown which parameter contributed most or predominantly to the established change

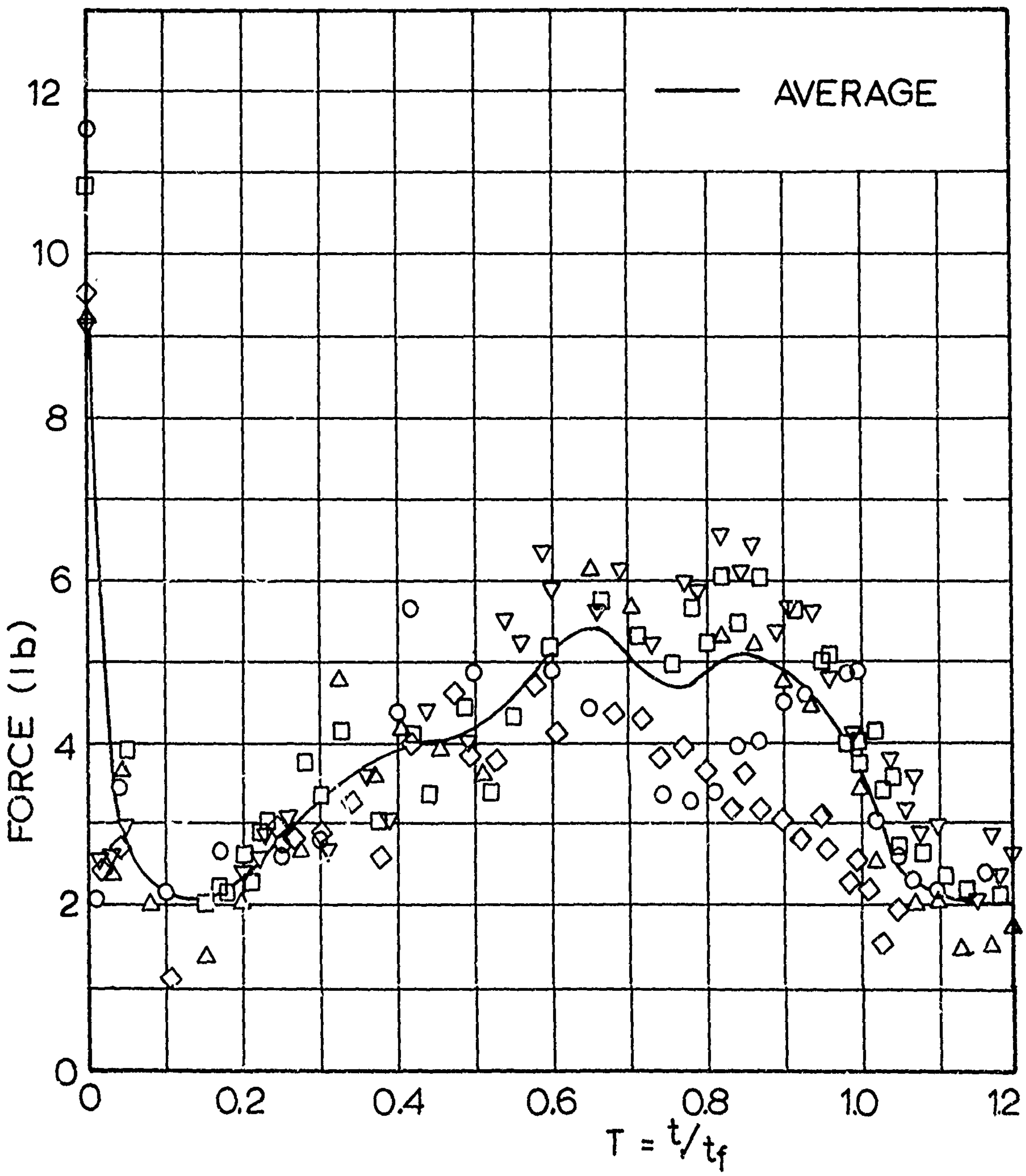


Fig 15 Wind Tunnel Experiments, System's Acceleration, 3.77-ft Ringslot Parachute W_s = 1.0 lb, m_i/m_s = 0.32, V_s = 50 fps

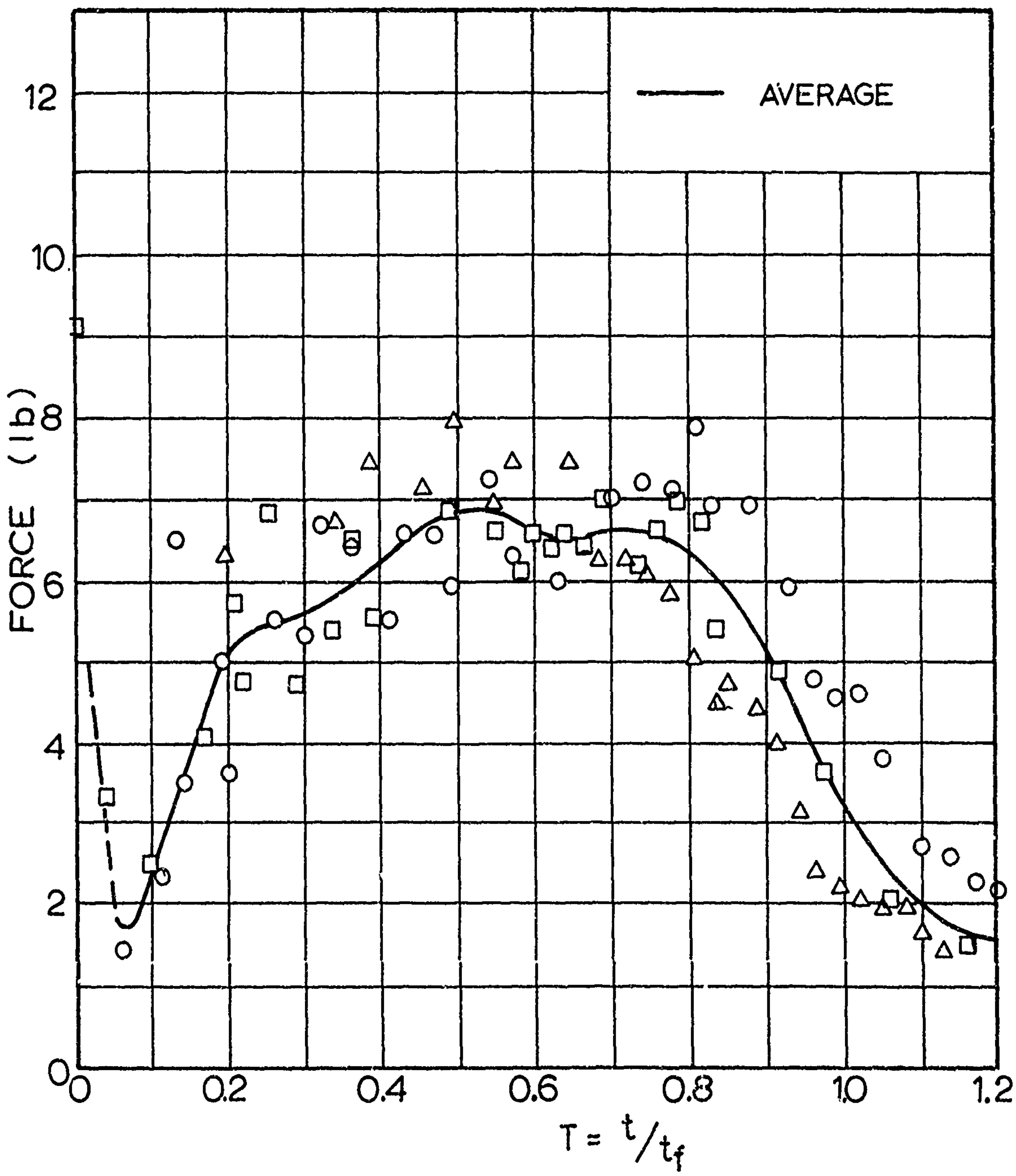


Fig 16 Wind Tunnel Experiments, System's Acceleration, 3.77-ft Ringslot Parachute, W_S = 1.0 lb, $^{m_i}/_{m_s}$ = 0.32, V_S = 70 fps

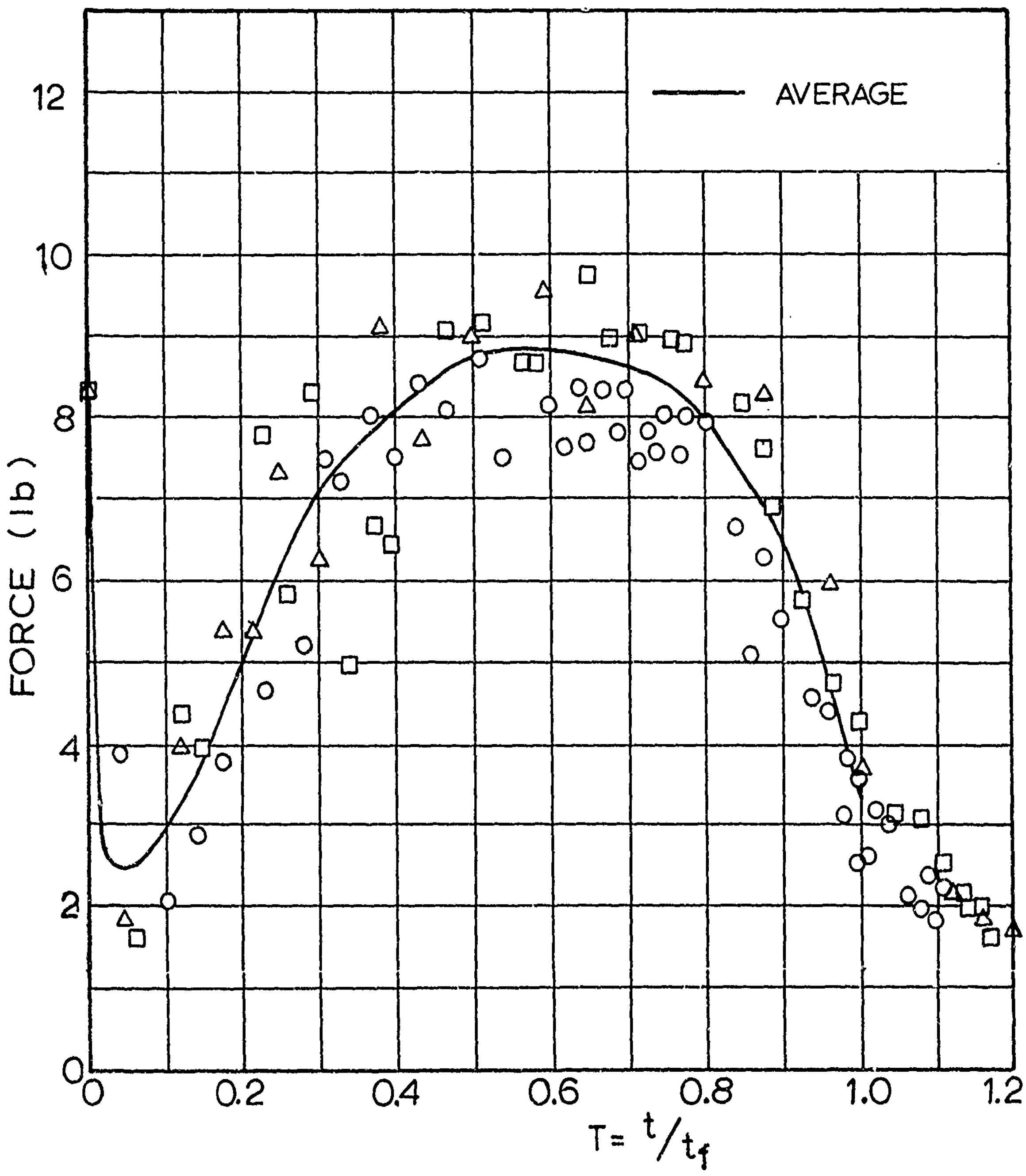


Fig 17 Wind Tunnel Experiments, System's Acceleration, 3.77-ft Ringslot Parachute, W_S = 1.0 lb, m_i/m_S = 0.32, V_S = 85 fps

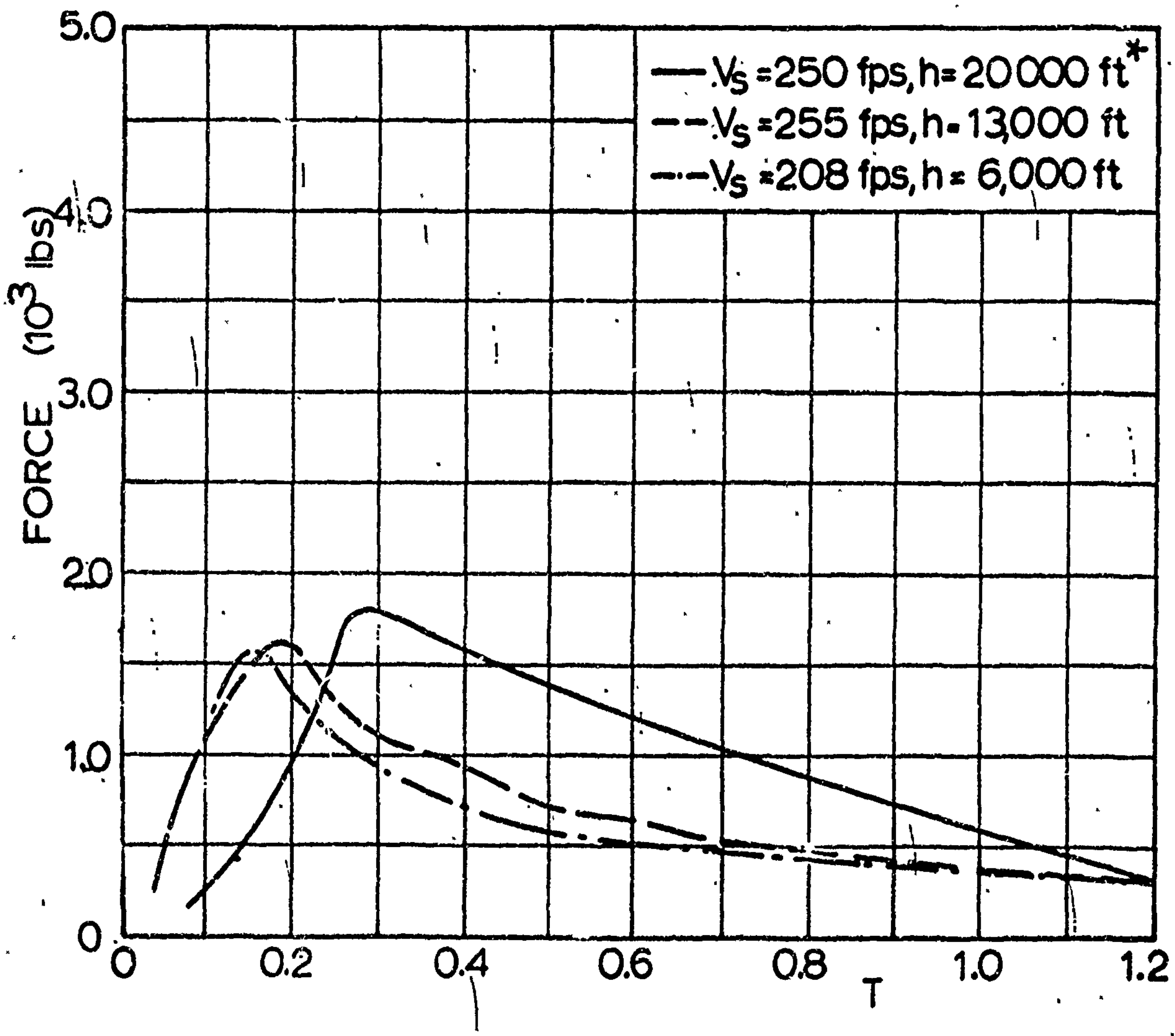


Fig 18 Characteristic Force-Time Histories of 32-ft Ringslot Parachutes at Nearly Constant Speed but Different Altitudes
*Mass Ratio, $m_i/m_s = 0.395$

in characteristic. They could also contribute equally to the shift in peak force. Unfortunately, a further study of this observation exceeds the scope of and possibilities under this task. The model tests in the wind tunnel and with the catapult merely established beyond doubt that at constant speed and air density the peak force shifted depending on mass ratio and surface loading.

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